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Power for Microsystems Strategic Technology Initiative Report on MAST Mission Power Requirements

by Brian Morgan and Sarah Bedair

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14. ABSTRACT

The development of Micro Autonomous Systems faces numerous technical hurdles. Beyond fundamental questions about locomotion at small scales and cooperative group behaviors is an ever-increasing need for efficiency and power, as each additional function on the system will require a finite amount of energy to execute its task. This report analyzes some of the basic power requirements for a mobile Microsystem in the context of a hypothetical military mission profile. The needs for various locomotion modalities, as well as system sizes, are compared with existing or emerging power sources to determine feasibility. A survey of systems being developed under the Micro Autonomous Systems and Technologies (MAST) Collaborative Technologies Alliance (CTA) is included to give the reader a concept of the breadth of power-consuming devices envisioned for future platforms.

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1. Introduction/Mission Definition

The Micro Autonomous Systems and Technology (MAST) Collaborative Technology Alliance (CTA) was initiated to spur basic research in small autonomous robots, particularly in four main areas: Microsystem Mechanics, Autonomous Processing, Microelectronics, and Integration. In order to focus its efforts, the Army proposed multiple scenario missions of increasing difficulty for the proposers to work towards: (1) small unit building search—flat, straight walls, no wind, etc; (2) a small unit cave search—potential for wind gusts, no regular surfaces to use as reference points; and (3) perimeter defense—longer required mission time and range and potentially harsh environments. The size ranges considered for this CTA were defined as "palm-size" and below, where no lower limit was specified.

This report will review the power required for both locomotion and electronic payloads for multiple robotic platform types in the context of an example mission. The basic scenario is assumed to be a small building unit search, particularly emblematic of Operation Iraqi Freedom. By sending in a robotic platform, fundamental information about the current state of the building can be ascertained before Soldiers are placed in harm's way. During a visit with Soldiers at Ft. Benning, GA, Dr. Joseph Mait (MAST CTA Collaborative Alliance Manager [CAM]) learned that the Soldier's concept of how best to use such systems would likely include separate and distinct periods of locomotion and surveillance/data sensing (*1*). For example, the robot would initially fly/crawl to a corner of a room, then stop and sense the surrounding environment. Upon sensing an "interesting" event, or after being given a command, the robot would stop sensing and locomote to a new position for a different view of the situation. Therefore, the hypothetical mission posed here is assumed to last ~21 min, divided between three perch locations of 5 min each, with ~2 min of ambulation/flying between perch locations. This leads to a minimum MAST system requirement of 6 min of crawling/flying, with an additional 15 min of sensing duties. However, Soldiers at Ft. Benning did indicate a desire for mission durations up to and exceeding 24 h, the majority of which would be in a sensing/perched mode where the power draw is widely variable depending on the sensors being used. For example, sampling deadly gases in the ambient environment may only require a sample rate of once every 10 min since the time constants governed by gas diffusion across a room may be on the order of minutes. While this 24-h goal is not addressed here, techniques such as low sampling rates, reduced communications, and sleep modes should enable longer missions with little impact on the overall energy requirement.

In the following sections, we will discuss locomotion options from the meso- to mm-scale, followed by a review of potential electronic and sensor payloads. We review available power sources in the context of the proposed mission. Finally, we will identify areas where the U.S. Army Research Laboratory's (ARL) expertise can make a significant contribution to the overall Power for Microsystems area.

2. Meso- to Mm-scale Locomotion

The power requirements for this hypothetical search/reconnaissance mission are markedly different depending on the system size and mobility choice (walking vs. flying). However, there are obvious capability differences (as well as potential hazards) between a flying platform and one limited to crawling on the ground. Anticipated solutions/requirements for mesoscale and mm-scale approaches are discussed.

Basic systems in the palm-size robotic scale that achieve multiple minutes of continuous flying time and tens of meters range using a standard Li-polymer battery can be purchased commercially at Toys R US for <$20 (see figure 1). Retrofitting this device with a few grams of sensors and a crude mobile sensor platform can be easily realized. This is one indication that commercially available power sources are sufficient to create flight at this mesoscale. However, the MAST-CTA aims to drastically improve nearly all aspects of such a device: mobility, stability, flying time, robustness, intelligence, etc.

Figure 1. Air Hogs R/C havoc heli, retail price $19.99 (Toysrus.com).

More advanced micro-air vehicles (MAVs) can be found in the academic community, such as the "TiShrov-1" (figure 2) developed at the University of Maryland (the MAST-CTA Micromechanics Center Lead). With a total diameter of only 13.5 cm and gross weight of 257 gm, this MAV is at the palm-size limit of interest to the MAST-CTA. It, too, uses a high energy density (800 mAh/50 gms) lithium polymer (LiPo) battery to drive an onboard 55 W brushless DC motor with an 8.6:1 gear ratio (*2*). This and other MAVs funded under an Army Research Office (ARO) Multidisciplinary University Research Initiative (MURI) typically have endurances in the 10–15 min range (*3*), perfect for our scenario. Recent small-scale experiments

(~15 cm) at UMD have shown that cycloidal rotors can be more efficient than the conventional rotor in hover (*4*, *5*) and will be studied extensively in the MAST effort. Biologically inspired meso-flying mechanisms are also being pursued, using flapping rotors such as those found in (*6*). Yet, these mesoscale examples show that flying systems that fulfill the 6 min of locomotion required by our mission have already been realized.

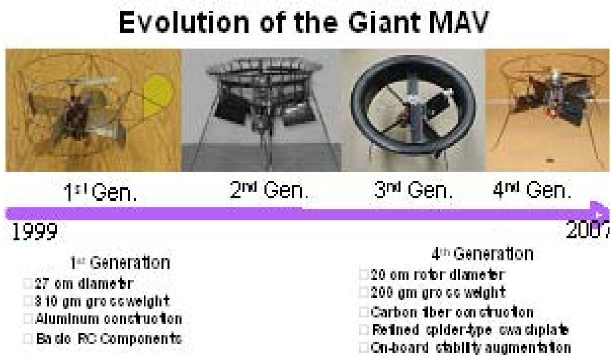

Table 1: Breakdown of component weights

	Ti-Flyer-1		Giant		Ti-Shrov-1	
Component	Weight g	% Total	Weight	% Total	Weight	% Total
Rotor System	30.5	8.9	18.3	7.6	25	49.7
Swashplate	20	5.8	8.1	3.4	12	4.7
Battery	106.2	30.9	53.3	22.2	53.3	20.7
Motor	52.7	15.3	52.7	22	16.9	6.6
Electronics & Servos	38	11	38	15.9	38	14.8
Structure	96.5	28.1	69.2	28.9	112	43.5
Total	343.9	100	239.6	100	257	100

Figure 2. MAVs developed at UMD (*2*).

Moving towards mm-scale robots offers significant advantages in both stealth (cockroach-size bots are less conspicuous than mesoscale MAVs) and capability (physical accessibility improves for small spaces). An alternative mission to the one being considered here, where mm-scale robots would be preferred, might be a search-and-rescue mission in a collapsed building, where large numbers of inexpensive robots could explore areas inaccessible or too dangerous for human investigation. Professor Ron Fearing's group at the University of California (UC)-Berkeley has long been a leader in mm-scale robotics, particularly using biomimetic principles in their approach to locomotion. Recently, the Fearing group developed a 3.5 cm, 3.1 g autonomous crawling robot (figure 3) designed to move at 1 cm/s (though assembly trouble prevented such a demonstration) (*7*). The onboard processor enables basic sensing and control. Methods were developed to wirelessly reprogram the processor according to changing conditions. The hexapod design was selected for stability, while locomotion was enabled by a novel chassis implementation incorporating high power density piezoelectric actuators. In order to drive the 200 V piezos, the 3.7 V battery voltage was boosted up using a 440 mg converter/controller board. Average current draw of 10 mA at this 3.7 V leads to an anticipated power requirement of only 37 mW during basic locomotion. Using the chosen lithium polymer battery by Kokam (650 mg, 20 mAh) leads to a potential running time of >2 h—more than 10 times longer than the required 6 min desired by the hypothetical reconnaissance mission (temporarily ignoring sensing power requirements, of course). However, this is still a walking/crawling robot with limited mobility, and significant research remains in order to enable the robot to navigate a complex terrain. A more attractive long-term solution is to fly over obstacles that are inhibiting to a crawling platform.

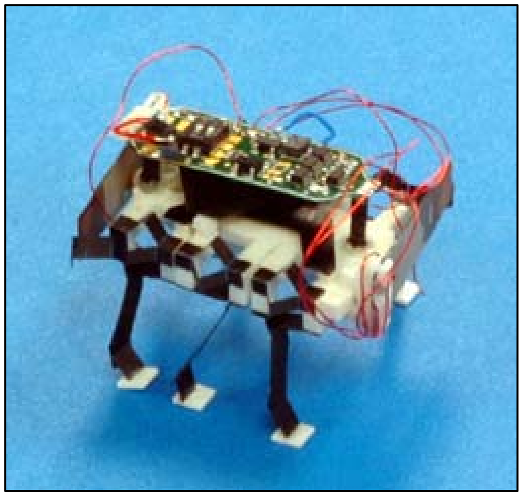

Figure 3. The 3 g robot from [97i].

Professor Robert Wood's group at Harvard University was the first to demonstrate positive flight in an mg-mechanical system, as shown in figure 4 (*8, 9*). The enabling technology was their development of extremely high power density piezoelectric actuators performing at >400 W/kg, which is approximately four times higher than the ordinary fly's muscles (*10–12*). Thus, the device was able to generate nearly twice its weight in thrust—approaching the thrust/weight performance of a real fly, which is typically three to five times its weight. The 3-cm flyer drew 10 mW and had an overall weight of only 60 mg; however, that did not include a power source or driving/control electronics. The Wood group's approximate breakdown of a future generation 120 mg flyer is shown in figure 5 (*13*), where an appropriate (i.e., stripped down) lithium polymer battery is estimated to weigh ~50 mg and should provide 5–10 min of flight (*8*) (equating to ~1 mWh capacity = 10 mW for 6 min). This flight range puts such a battery at the very minimum of usability for our mission scenario, but power requirements could change dramatically depending on atmospheric conditions. Thus, basic locomotion of mm-scale flyers should be achievable, but flight time and mobility is definitely limited at this reduced scale, where the power source already makes up half the body weight of the system.

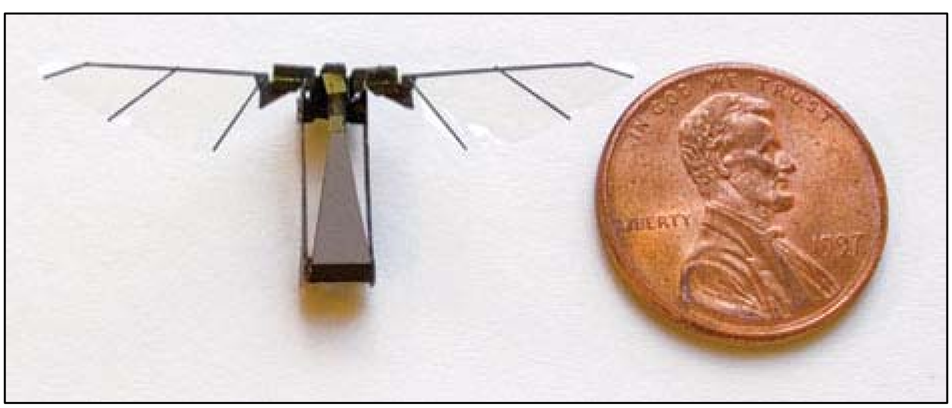

Figure 4. Miniature flyer from Professor Wood's group at Harvard (*8*).

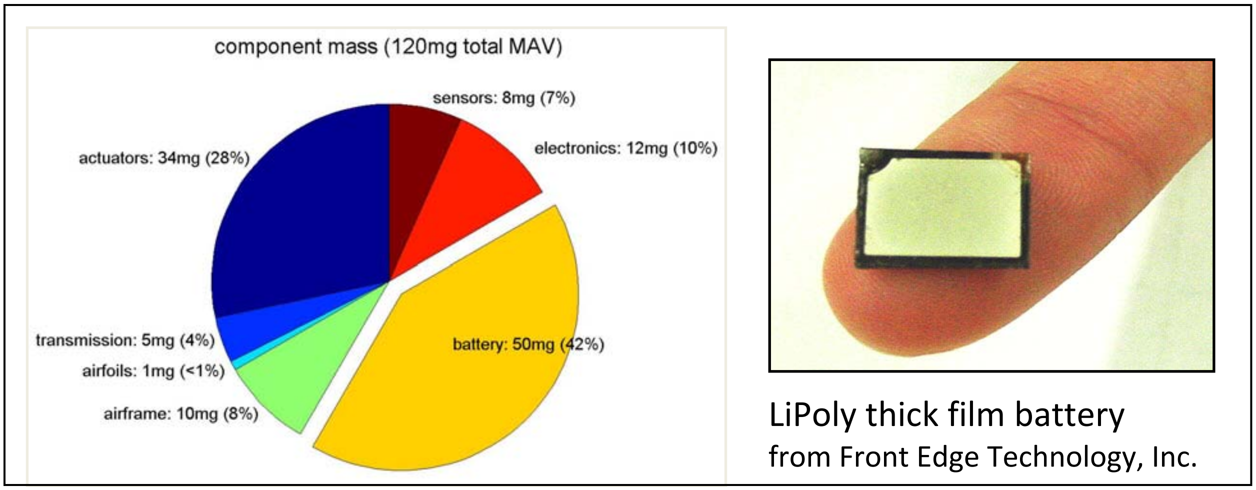

Figure 5. Mass budget breakdown for hypothetical 120 mg MAV (*13*).

3. Electronic/Sensor Payloads

One major challenge for small autonomous systems is the wide range of power requirements for the sensors and actuators being developed as part of the MAST program. As a first step to this daunting power problem, we conducted a survey of the MAST consortium members and ARL researchers involved in this area to identify the power needs of various sub-systems. While this survey is in its infancy, early results are shown in table 1. The voltage and power values from table 1 are also plotted in figure 6 for convenience and further illustrate that the power conversion specifications are "all over the map." In other words, from a power supply engineer's perspective, figure 6 poses a challenging design problem where traditionally sub-gram specifications were not a requirement. At a first glance, however, completely autonomous platforms with minimal intelligence are feasible, as will be illustrated in figure 6.

Table 1. Early survey results from MAST participants and ARL researchers.

Principle Investigator	System	Used During Locomotion or Sensing?	Current / Projected Technology (0-5 yrs)	
			Voltage Required	Average Power
ARL	Bugbot motor	Locomotion	3.3, 5.0 VDC	1.5 W
ARL	CPU	Locomotion	1.5, 2.8, 3.3 VDC	0.08 W
ARL	Communication electronics	Locomotion	3.3 VDC	0.05 W
ARL	Meso-auxiliary sensors (camera, audio, etc.)	Locomotion	1.5, 2.8 VDC	0.03–0.05 W
Harmon (UMD)	Wingbot motor	Locomotion	7.4, 11.1 VDC	135 W
Wood (Harvard)	Microrobotic fly	Locomotion	200–300 VAC	10–50 mW
Najafi (UMich)	HAIR sensors	Locomotion	5 VDC	50 mW
Najafi (UMich)	HAIR inertial sensor	Locomotion	10 VDC	50 mW
ARL	Scorpion	Locomotion	20–50 VDC	1–200 mW
Fearing (UC-Berkeley)	DC motors for running/flight	Locomotion	4 VDC	0.5–5 W
Fearing (UC-Berkeley	Piezos for running/flight	Locomotion	300 VAC	30–300 mW
Fearing (UC-Berkeley	Piezos for steering	Locomotion	300 VAC	10 mW
Fearing (UC-Berkeley)	SMA actuators for steering	Locomotion	1–10 V	100 mW
Smela (UMD)	Dielectric elastomer actuator	Locomotion	500–5000 VAC	1–10 0mW
Barrows (Centeye)	Vision/optical flow sensors	Locomotion	3.3–5 VDC	1–20 mW
Sylvester (UMich)	Low power processor	Locomotion & Sensing	0.2 VDC	3–30 mW
Gianchandani (UMich)	Radiation detector	Sensing	700–1200 VDC	100–200 µW
Flynn (UMich)	Digital TX	Sensing	1.2 VDC	100 mW
Najafi (UMich)	HAIR actuators	Sensing	100–200 VDC	100 mW
Gordenker (UMich)	Mercury micro-gas chromatograph: column	Sensing	2 VDC	20m W
Gordenker (UMich)	Mercury micro-gas chromatograph: preconcentrator	Sensing	80 VDC	80 W (for 3 s)
Gordenker (UMich)	Mercury micro-gas chromatograph: temp sensor	Sensing	5 VDC	5 mW
Gordenker (UMich)	Mercury micro-gas chromatograph: sensor array	Sensing	12 VDC	~18 mW
Gordenker (UMich)	Gas chromatograph pump: for now commercial	Sensing	6 VDC	900 mW
Amir (UMich)	Switchable resonator/filters	Sensing	15 VDC	15 uW
East (UMich)	Mesoscale radar	Sensing	12 VDC	3.6 W
East (UMich)	Miniaturized 77 GHz radar	Sensing	1–2 VDC	500 mW
Flynn (UMich)	Low power 77 GHz radar	Sensing	1.5 VDC	10 mW

Note: UMD = University of Maryland and UMich = University of Michigan.

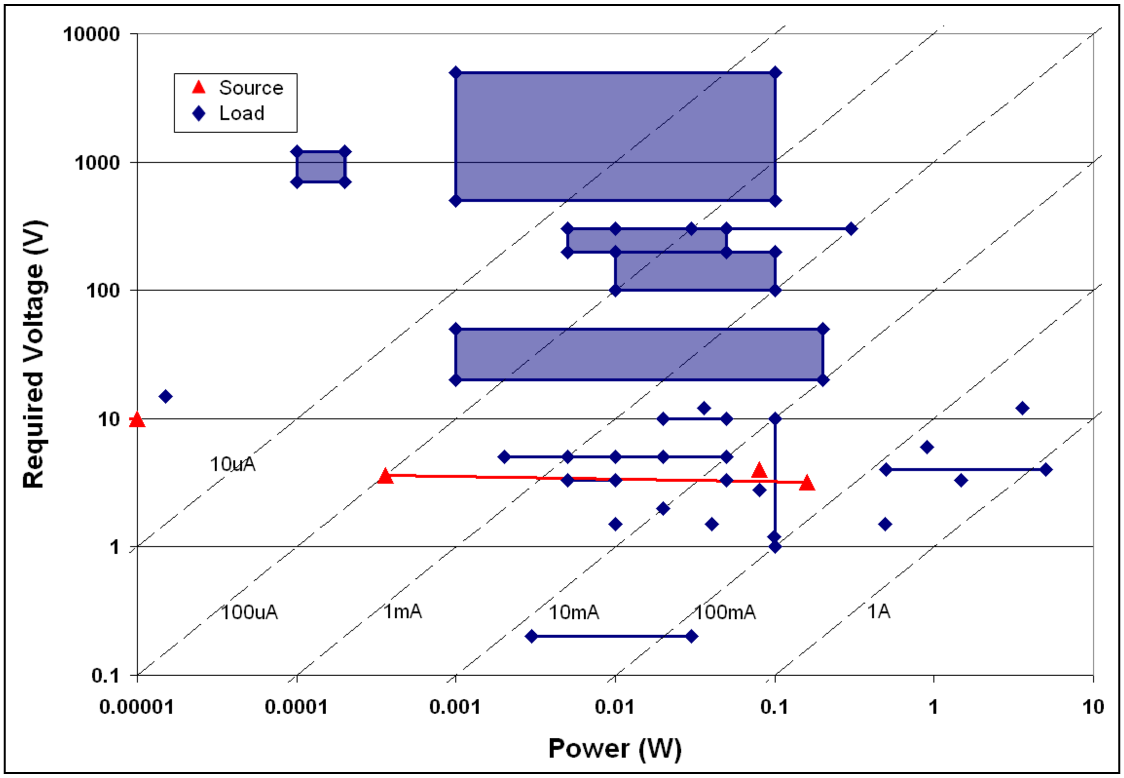

Figure 6. MAST power survey early results.

With power requirements on the order of tens of mW, many of the responses/estimates shown in table 1 would be most appropriate at the mesoscale, or perhaps for a crawling mm-scale robot. Given our hypothetical mission requiring 15 min of sensing time, a conservative estimate of the total energy required through the multiple perch locations for either meso-systems or crawling mm-scale systems is only ~25 mWh (100 mW × 15 min)—easily provided by commercial batteries like the Kokam lithium polymer battery discussed in section 2 (*7*).

However, miniaturization and power reduction of these and other sensors/actuators is a major MAST thrust and becomes increasingly important when considering a mm-scale flying platform (recall that the weight budget in figure 5 leaves only 8 mg for sensors and 50 mg for battery). Basic functioning of a mm-scale platform would likely require a minimum of one sensor, one processor (for navigation), and a method of communication. Low power microcontrollers that can operate at less than 400 μW (EM6812 from EM Microelectronics, 120 μA at 3 V) are commercially available. Efficient data transmission is a challenging obstacle, though many groups have been exploring this area. Most notably, Professor Jan Rabaey (UC-Berkeley) and his students have demonstrated 98% efficient antennas and >40% transmitter efficiency when operating between 0.85–1.45 W. The targeted data rates were 330 kbs and when implemented in a 0.13 μm complementary metal-oxide semiconductor (CMOS) process took only 0.8 × 1.85 mm^2 (*14*). Assuming the density of silicon to be ~2.3 g/cm^3, and that the die is 500 μm thick, the total weight of such a transmitter would be <2 mg. One drawback is the range of operation, where received power is only –39 dBm at 0.5 m or –54 dBm at 10 m (*14*). Commercial sensors can be found that operate on as little as 80 μW while measuring both temperature and relative humidity in a compact form factor (7.5 mm × 5 mm × 2.5 mm) (*15*). Assuming all of these components were simultaneously operating with moderate frequency, an average power consumption of ~1 mW should be attainable. Thus, for our mission, 15 min at 1 mW requires another 0.25 mWh of energy on top of the ~1 mWh required for flying. For a conservative target, a total energy of ~2 mWh in a 50-mg package leads to an energy density requirement of ~40 Wh/kg. Individually, these systems are extremely basic, but a large number of systems could be deployed that would work in concert to gain a full spectrum of information.

4. Power Options/Limitations

We reached two basic conclusions with regard to mm-crawling systems and thin film battery power density:

- *For meso-flying and mm-crawling systems, current power sources have sufficient power density and energy density to execute basic missions with 10–20 minute durations, <u>as long as we assume ideal power delivery (i.e., 100% efficient power conversion and management)</u>.*
- *For micro-flying systems, current research suggests thin film batteries will soon achieve the required power density for autonomous flight (1–5 min range), but the mission duration and/or capability of individual flyers will be limited by inefficient power delivery and small payload capacity.*

Combining our knowledge about the electronic and mobility power requirements for the mm-scale crawling robot is quite encouraging. Recall that the Fearing robot (*7*) requires only ~37 mW for basic mobility. If we assume the power draw in a "real" environment will increase significantly to 100 mW (like in the sensing mode) in order to perform basic tasks during locomotion (like obstacle avoidance or overcoming friction), an average power draw of 100 mW throughout the entire 21-min mission seems realistic. The resulting ~35 mWh should be easily supplied by the ~70 mWh battery currently in use. This indicates that with a safety factor of two, *the hypothetical mission could be successfully completed by a mm-scale crawling robot using a commercially available battery*. Since the analysis assumes a locomotion time (rather than distance), a sanity check is required to ensure that the distance covered is physically significant compared to a typical room. Though few demonstrations have been made, realistic speeds for such robots are estimated to be >1 body length per second. For a 3-cm robot, 2 min of straight operation would yield >3.6 m of movement—enough to walk across a common room. Improvements in power source energy density will have direct benefit to mission duration/lifetime, and thus ultimate utility to the Soldier. However, improving the energy density of battery technology at this scale is a widely researched area in industry and would require an immense investment by ARL in order to make a significant contribution. If total energy capacity (i.e. mission lifetime) becomes a problem, the addition of energy scavenging capabilities like solar cells could greatly increase mission range/duration. However, its benefit may only be mission dependent.

For a mm-scale flyer, the power source and delivery are larger problems. As shown previously, basic operation/liftoff may be feasible using current state-of-the-art components and research demonstrations; however, this feasibility is at the cost of intelligence and likely mission duration. As a general rule, we must keep in mind that the fundamental delivered mechanical power required for wall climbing animals is estimated to be 10 W/kg (*16*), while approximately 100 W/kg is required for hovering flapping flight (*17*)—one of the most power-intensive flight modes. An energy density of ~40 Wh/kg, as noted previously, must also be targeted as a minimum threshold, which is consistent with Rob Wood's estimate of a 50-mg battery providing 10 mW for 5–10 min of flight (i.e., 200 W/kg at 20-40 Wh/kg). For comparison, commercially available lithium ion batteries in the few-hundred-gram range can output >200 W/kg (*18*) but have difficulties scaling down to the required sub-gram level.

From a survey of the leading thin film battery companies, Front Edge Technology (www.frontedgetechnology.com) offers a 20 mm × 25 mm × 0.3 mm product with a 1-mAh (3.5 mWh) battery. Assuming a density of 2.5 g/cm^3 (similar to silicon), leads to ~375 mg weight; a current output of 10 mA (~35 mW) gives a power density of ~93 W/kg, but an energy density of only ~9.3 Wh/kg—falling short of our target metrics. However, leading researchers (including Dr. Nancy Dudney) at Oak Ridge National Laboratory, which license parts of its technology to Front Edge, estimate that if packaging were neglected, a 1-mWh battery could theoretically be only 2.5 mg, leading to 400 Wh/kg and 1 kWh/liter (*19*). With demonstrated power draws of 10 mW/cm^2 and an estimated weight of 9–27 mg/cm^2 after assuming a 3× packaging penalty (*19*), such thin film batteries should exhibit power density of 370–1100 W/kg, easily meeting Professor Wood's flyer requirements. DARPA also has a program focused on mm^3-scale power sources ("Micro Power Sources," run by Ms. Sharon Beermann-Curtin [DARPA BAA 06-33]) that is targeting between 100–700 W/L, which should result in 40–280 W/kg sources (again assuming 2.5 g/cc density). While batteries typically sacrifice energy density when run at such high-power densities, scavenging energy options are also possible (like solar cells on the wings) in order to extend mission lifetime.

Yet inherent battery or power source performance is only part of the solution—one must also efficiently deliver the available power into the desired format for use by the actuators. Miniature autotransformer-based power converters developed by Professor Wood's group operate at <50% efficiency when boosting 100–200 mW up to the desired 200 V (*21*). Not only is this 80 mg converter approximately 10 times larger than Professor Wood's requirement, but this low efficiency puts twice the burden on the power source. Thus, either the flight time is cut in half, or a power source with twice the energy density than originally anticipated must be found. This gaping technology hole was the driving motivation behind the *Power for Microsystems Strategic Technology Initiatives' (STI)* initial focus on efficient ultra-miniature power converters, as *improvements in conversion efficiency become analogous to improvements in battery performance*.

5. The Way Ahead

Given our scenario-based evaluation of power requirements and emerging commercial energy sources, we now view the overall challenge of Microsystem power in the context of four interrelated requirements, in relative order of their importance:

1. *Source power density → one must have sufficient power available relative to the system size in order to meet fundamental requirements for locomotion/flight;*
2. *Actuator power density/efficiency → even though the power may be available, one must efficiently convert it to mechanical work to actually crawl/fly (this includes electrical conversion as covered in our STI);*
3. *Source energy density → only once you are moving/off the ground should you worry about flight time/mission duration;*
4. *Payload overhead → depending on how easily the first three requirements are met, tradeoffs can be made regarding the available power/weight overhead for sensors etc.*

Requirement #1 is largely being addressed by the thin film battery industry and success appears to be near-term (if not already here), regardless of potential further investment by ARL. For Requirement #2, efficient delivery of actuator power into controlled mm-scale mechanical motion is an active area of research in the MAST CTA Micromechanics Center (primarily Professors Wood and Fearing). MAST research focuses on specialty gear, transmissions, and actuators. However, embedded in the delivery system is *a pressing need for power conversion architectures capable of supplying the requisite voltages (>200 Vac) in ultra small weight/volume* (see figure 5 where only 12 mg is saved for "electronics"), *which to date does not exist.* Requirements #3 and #4 are inherently interrelated, as one can often trade functionality for lifetime and vice versa. In particular, energy density could be improved with energy harvesters (i.e., add a solar cell), though the wide range of potential operating environments will limit their effectiveness. Hybrid sources with high energy density (such as a battery/micro-fuel cell hybrid) would be attractive if miniaturization challenges such as fuel storage and balance of plant difficulties can be addressed.

In summary, due to existing mesoscale batteries and emerging high performance thin film batteries, the power source does not appear to be a fundamental roadblock to the successful development of basic autonomous meso- and mm-scale robots. However, our survey of the

MAST consortium, leading academics, and industrial power engineers has identified a severe lack of existing research in ultra-compact high-voltage power conversion for high power density actuation (see requirement #2 above). Thus, *power conversion/management at the micro-scale continue to be the primary areas where new high impact research can be led by ARL*—hence the Power for Microsystems STI's initial focus.

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List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
ARO	Army Research Office
CAM	Collaborative Alliance Manager
CMOS	complementary metal-oxide semiconductor
CTA	Collaborative Technology Alliance
LiPo	lithium polymer
MAST	Micro Autonomous Systems and Technology
MAVs	micro-air vehicles
MURI	Multidisciplinary University Research Initiative
STI	Strategic Technology Initiatives
UC	University of California
UMD	University of Maryland
UMich	University of Michigan

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